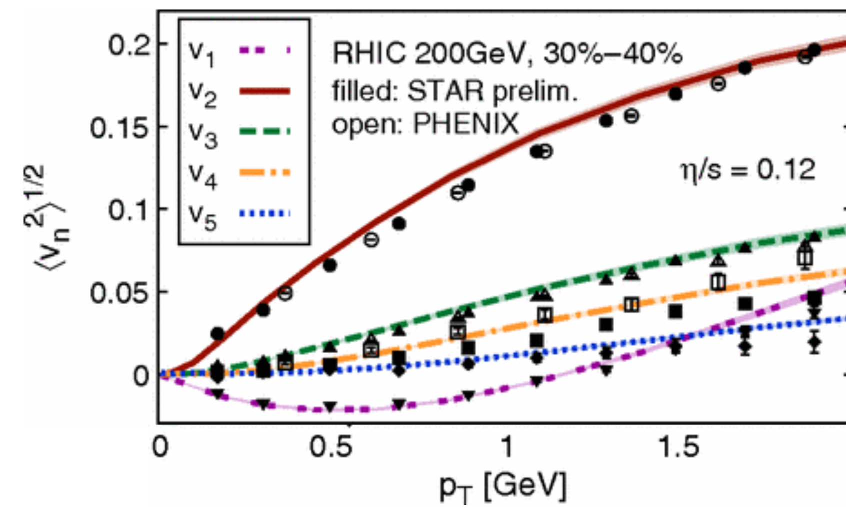
Collectivity in Small Systems at RHIC

Kurt Hill
University of Colorado

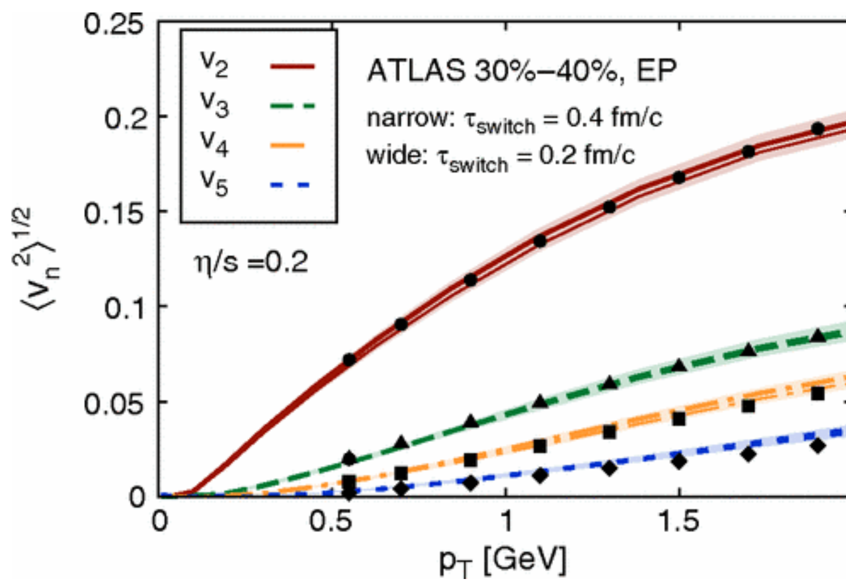
RHIC AGS Users' Meeting
June 8 2016

Collectivity in A+A Collisions

Hydro has become the standard picture



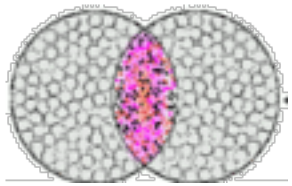
Single model describes data from RHIC and LHC

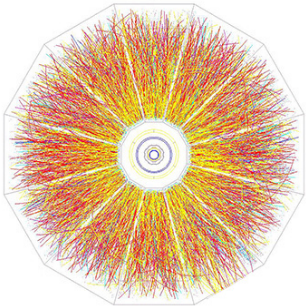


Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

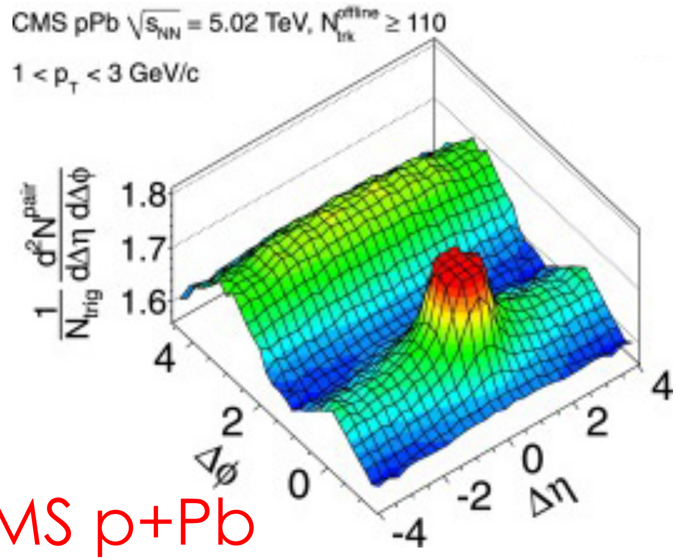
Hydrodynamic Evolution

Initial state energy distribution → Pre-equilibrium dynamics → Equilibrated (QGP) flow → Hadron gas



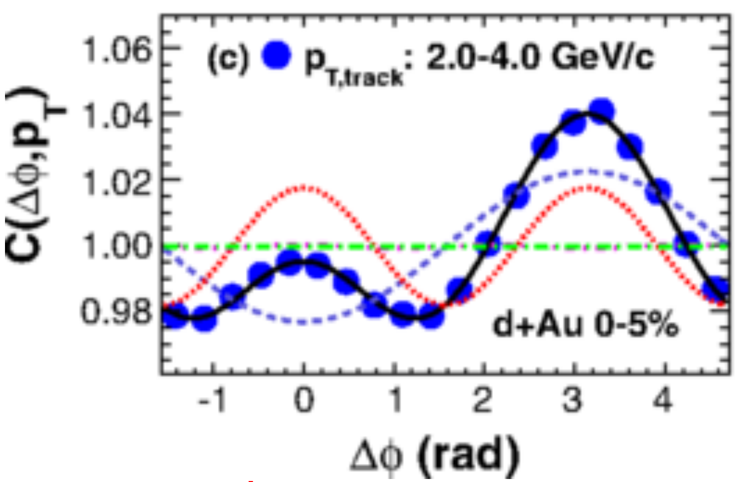


Collectivity in Small Systems



Phys. Let. B 718 (2013) 795–814

CMS p+Pb



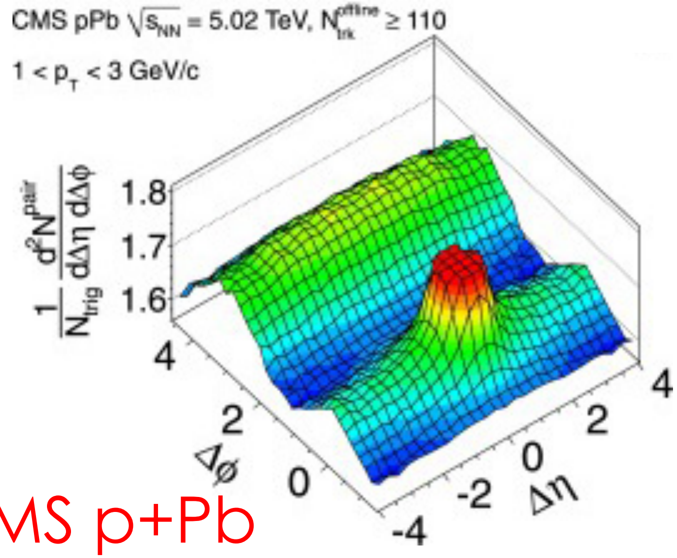
Phys. Rev. Lett. 114, 192301

PHENIX d+Au

Recent Studies at both RHIC and LHC hint at collective behavior in systems once thought too small

Collectivity in Small Systems

Phys. Let. B 718 (2013) 795–814



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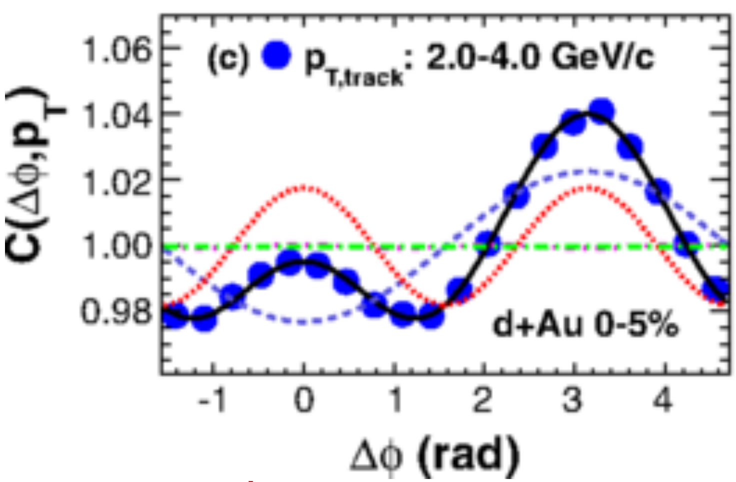


Phys. Rev. Lett. 114, 192301

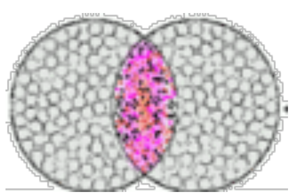
PHENIX d+Au

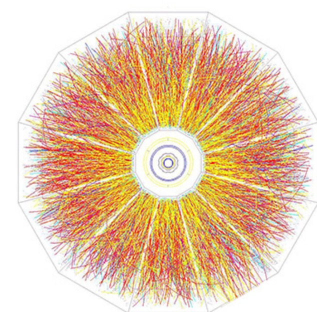
Recent Studies at both RHIC and LHC hint at collective behavior in systems once thought too small

New channels open to test the Hydro picture

Hydrodynamic Evolution

Initial state energy distribution → Pre-equilibrium dynamics → Equilibrated (QGP) flow → Hadron gas

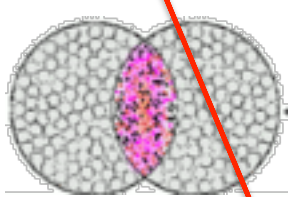


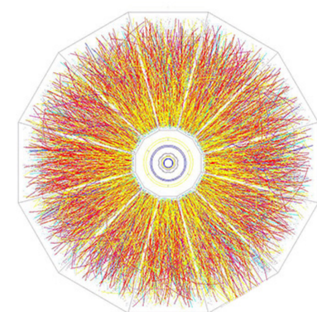


Can small systems help us understand how initial geometry and energy deposition translate to final state particle distribution?

Hydrodynamic Evolution

Initial state energy distribution → Pre-equilibrium dynamics → Equilibrated (QGP) flow → Hadron gas

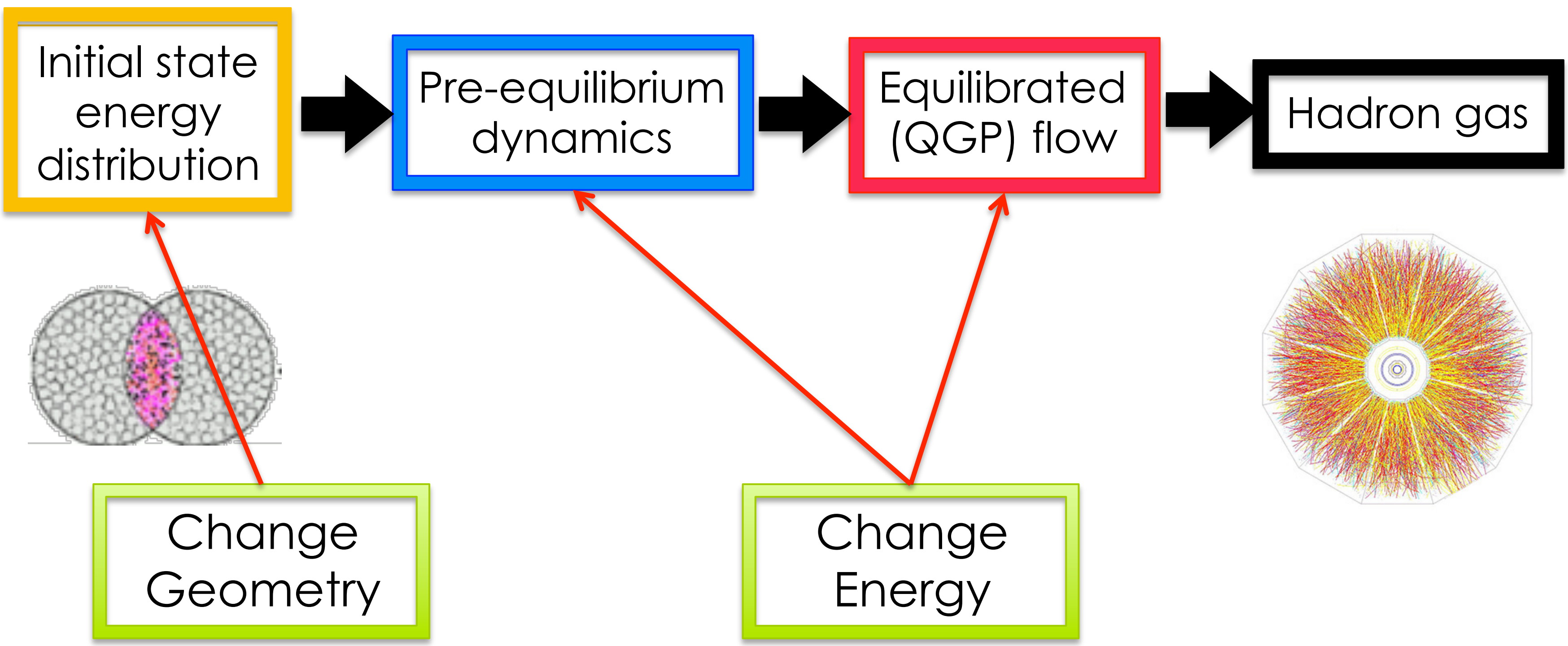




Change Geometry

Can small systems help us understand how initial geometry and energy deposition translate to final state particle distribution?

Hydrodynamic Evolution



Can small systems help us understand how initial geometry and energy deposition translate to final state particle distribution?

Small Systems Experiments

Change Geometry

Change Energy

Small Systems Experiments

Change Geometry

Change Energy

- Control initial geometry of projectile
- Measure system response via final state anisotropies

Small Systems Experiments

Change Geometry

Change Energy

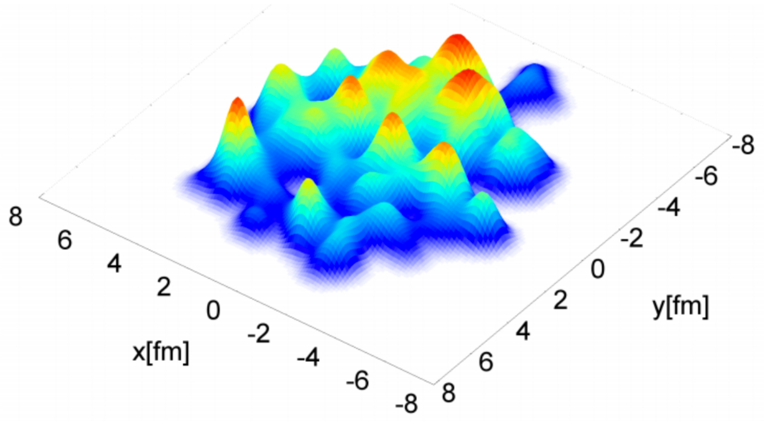
- Control initial geometry of projectile
- Measure system response via final state anisotropies

Collision geo $\xrightarrow{\text{Model}}$ Initial anisotropy

Initial Conditions

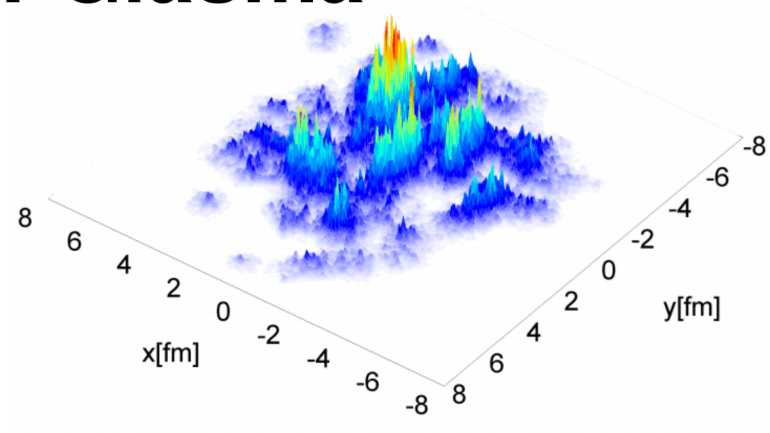
Schenke, Tribedy, Venugopalan: Phys. Rev. Lett. 108, 252301

MC Glauber



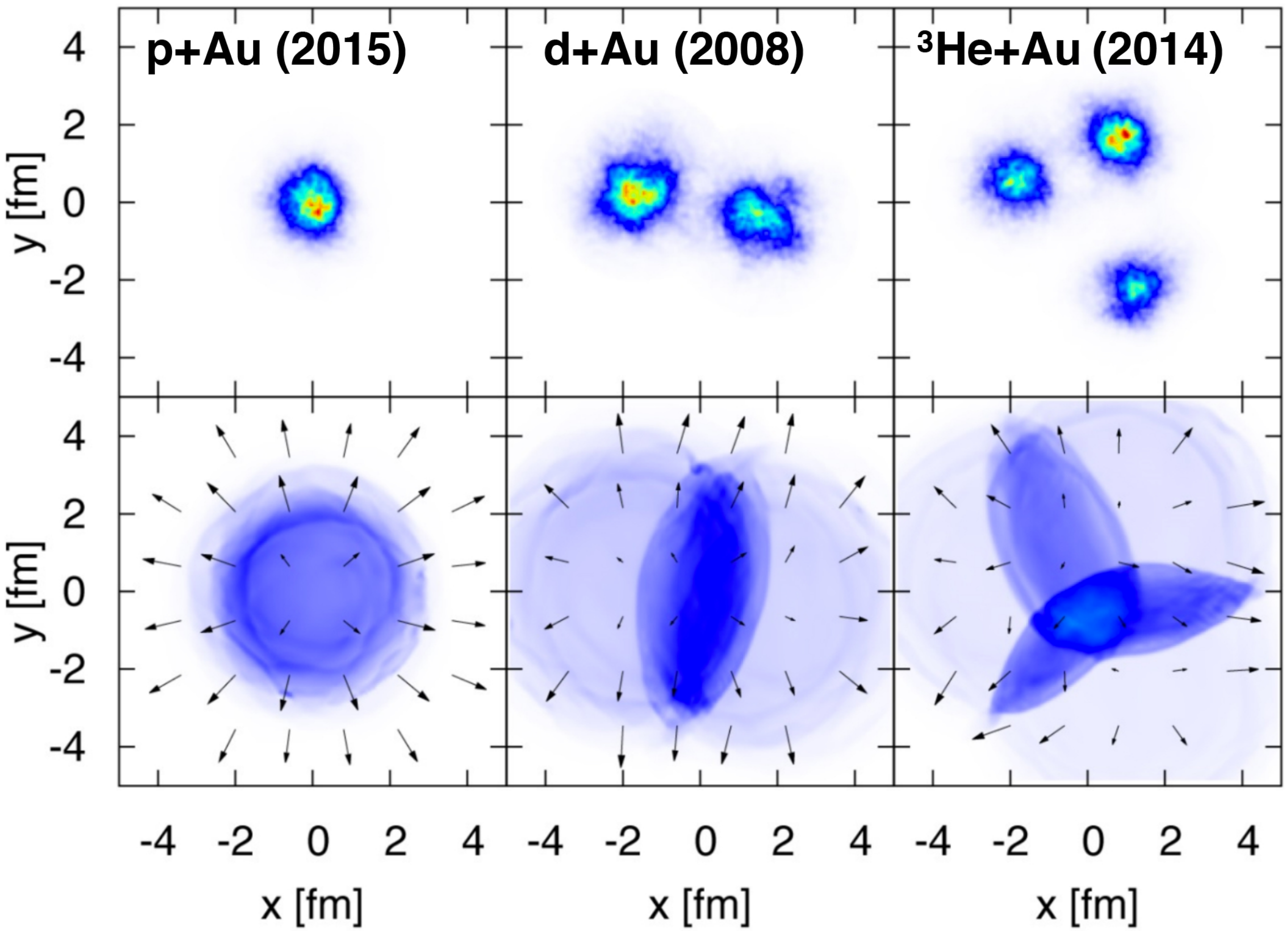
- Fluctuations in nucleon coordinates
- Smear energy deposition by Gaussian
- Use all participants

IPGlasma



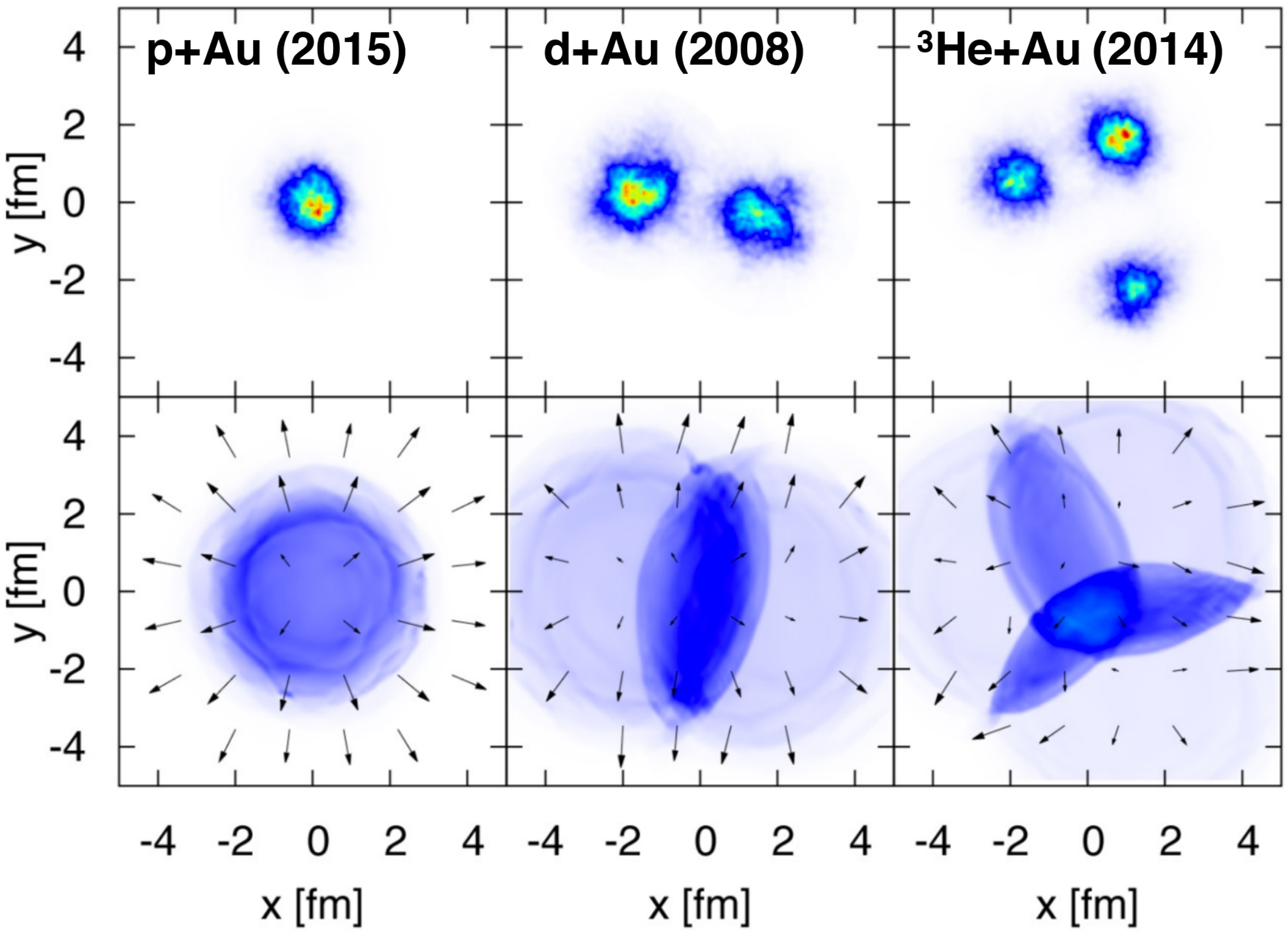
- Fluctuations in nucleon coordinates
- <u>Fluctuations in color charge within nucleons</u>
- Look at region where nucleons overlap

Geometry Engineering at RHIC



Courtesy of Björn Schenke

Geometry Engineering at RHIC



Courtesy of Björn Schenke

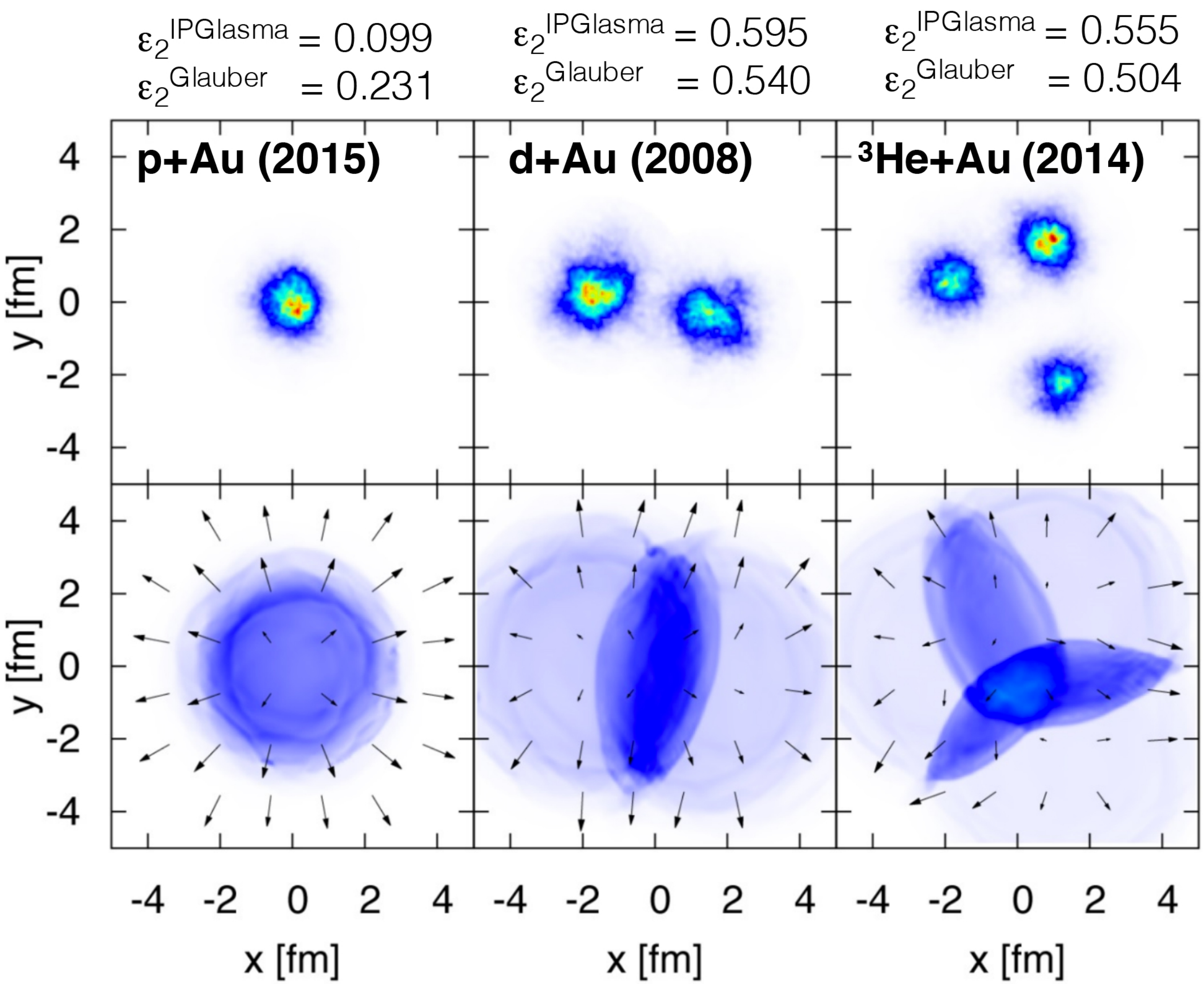
Quantify initial anisotropy (MC)

$$\varepsilon_n = \left(\sqrt{\langle r^2 \cos(n\phi_{\rm part})\rangle^2 + \langle r^2 \sin(n\phi_{\rm part})\rangle^2}\right) / \langle r^2\rangle$$

Compare with measured anisotropy

$$v_2 = \frac{\langle \sum \cos 2(\phi - \Psi_2)\rangle}{\mathrm{Res}(\Psi_2)}$$

Geometry Engineering at RHIC



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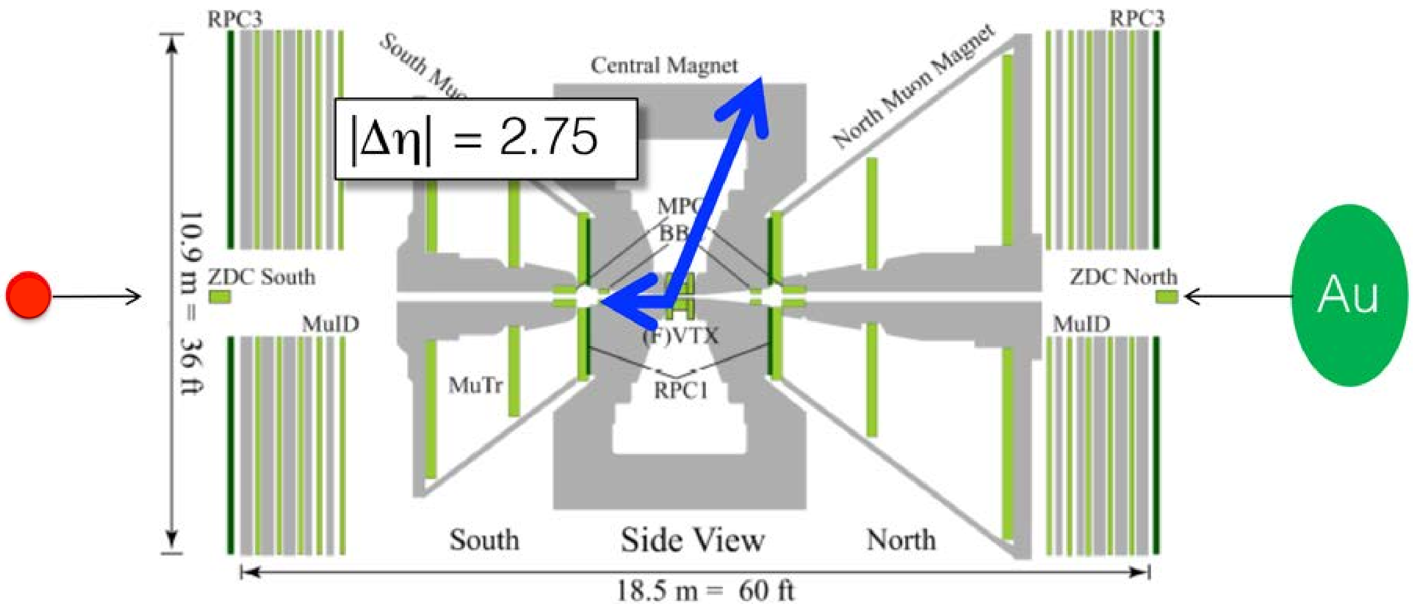
For Ideal hydro

$$\boxed{V_2 \propto \varepsilon_2}$$

PHENIX Long Range Correlations

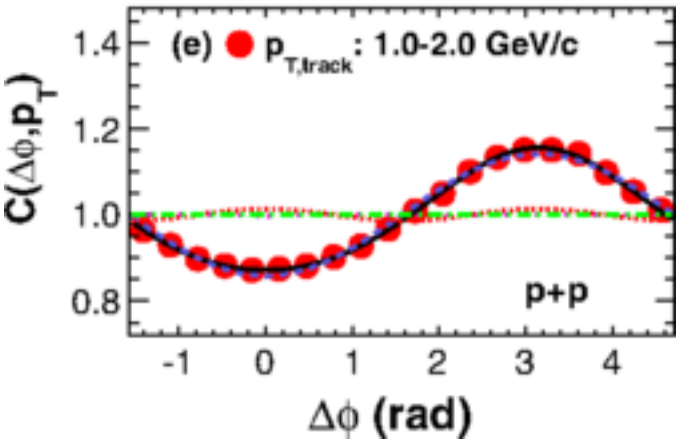


$$S(\Delta\phi, p_T) = \frac{d(w_{\text{tower}} N^{\text{track}(p_T)\text{-tower}}_{\text{same event}})}{d\Delta\phi}$$

$$C(\Delta\phi, p_T) = \frac{S(\Delta\phi, p_T)}{M(\Delta\phi, p_T)} \frac{\int_0^{2\pi} M(\Delta\phi, p_T) d\Delta\phi}{\int_0^{2\pi} S(\Delta\phi, p_T) d\Delta\phi}$$

Mixed event

PHENIX Long Range Correlations



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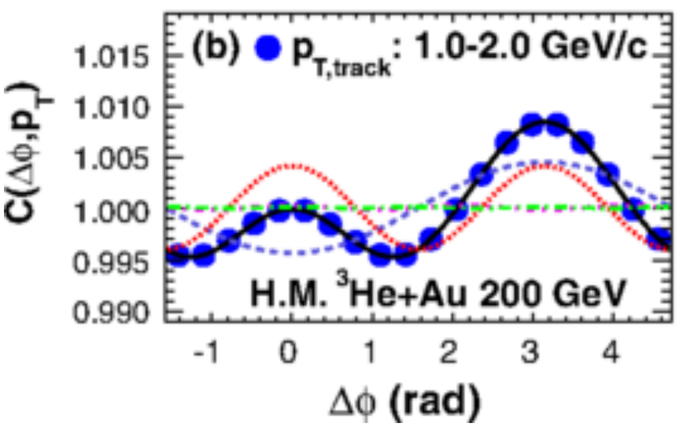
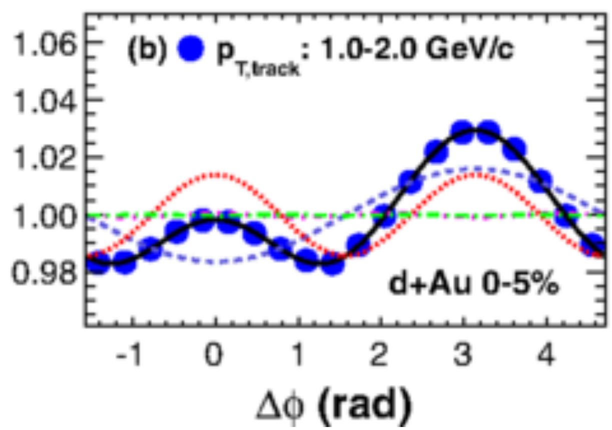
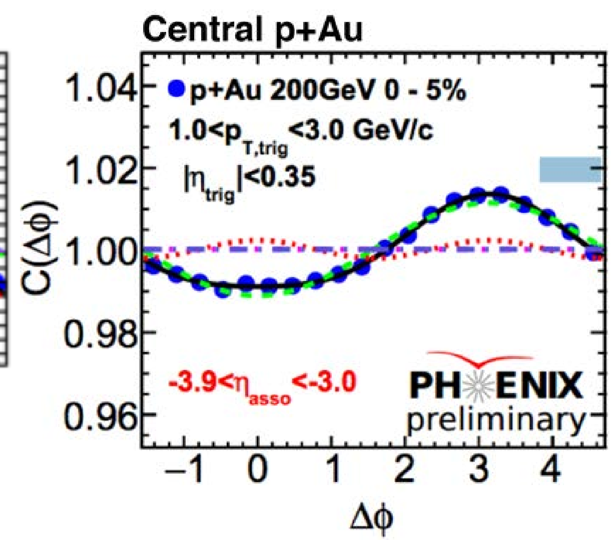
$|\Delta\eta| > 2.75$





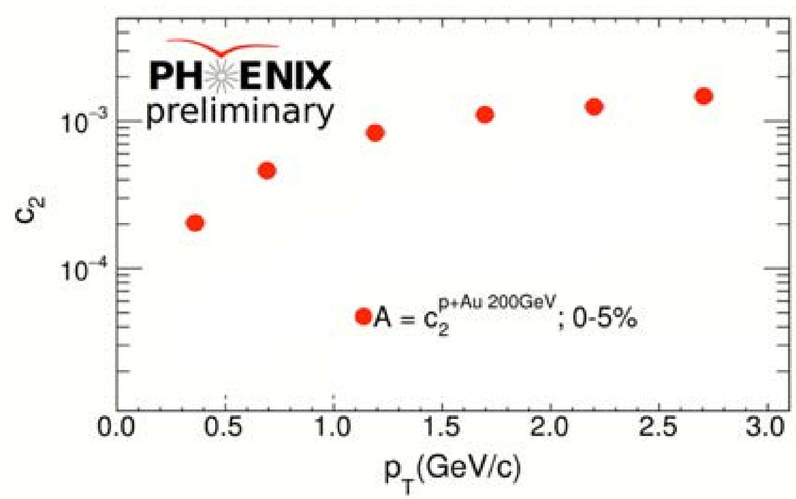


Estimating Non-Flow

$$c_2(p_T) = c_2^{\text{Non-Elementary}} + c_2^{\text{Elementary}}$$

Flow

Dijet fragmentation/resonance decays



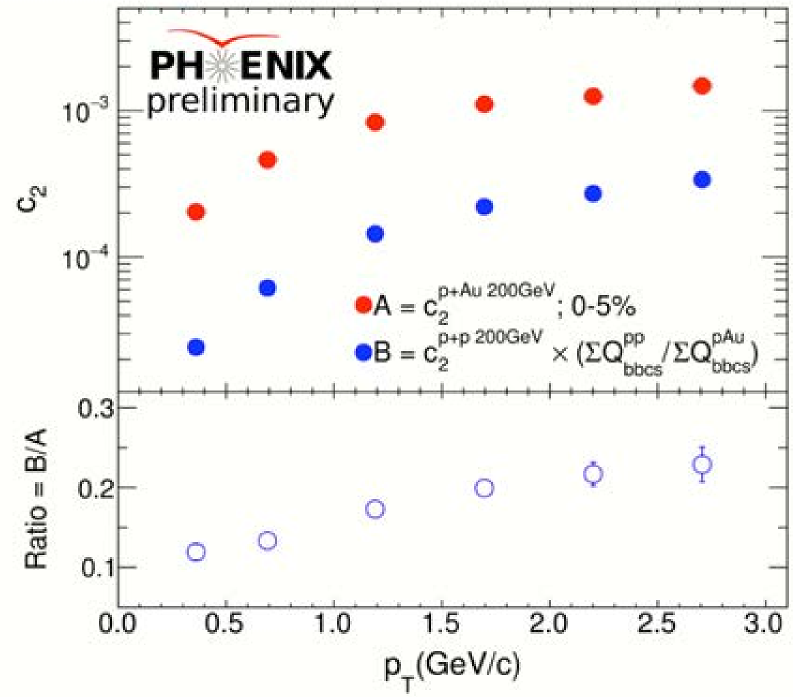
Estimating Non-Flow

$$c_2(p_T) = c_2^{\text{Non-Elementary}} + c_2^{\text{Elementary}}$$

$$c_2(p_T) = c_2^{\text{Non-Elementary}} + c_2^{p+p} \times \frac{\text{Charge at Forward } \eta \text{ in p+p}}{\text{Charge at Forward } \eta \text{ in p+Au}}$$

Use p+p as a reference

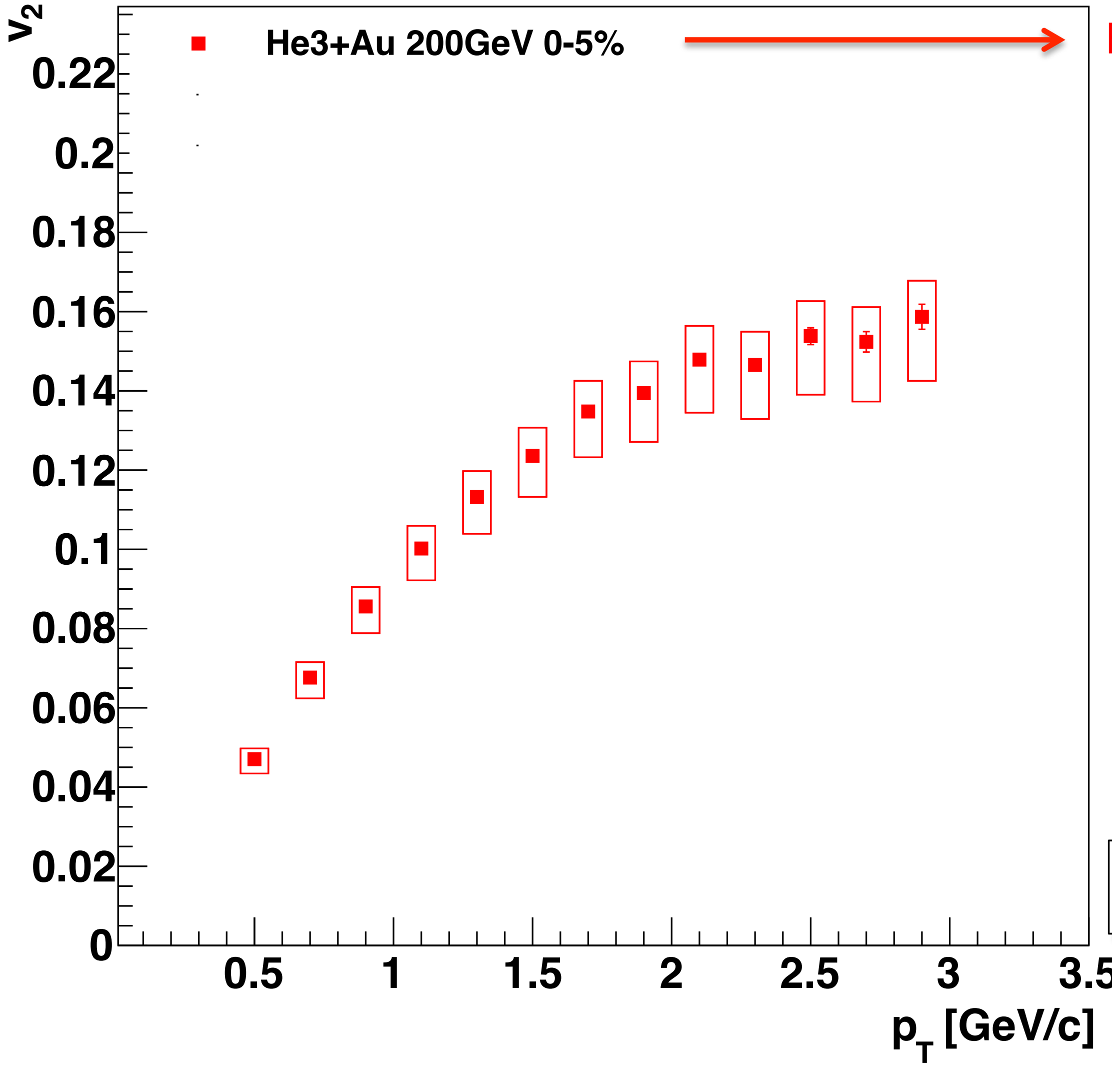
Scale it down by relative multiplicity



Factored into measurement as systematic uncertainty only

Elliptic Flow – Event Plane Method

PHENIX Data



Phys. Rev. Lett. 115, 142301 (2015)

$$v_2 = \frac{\langle \sum \cos 2(\phi - \Psi_2) \rangle}{\mathrm{Res}(\Psi_2)}$$

Resolution *Res* (Ψ) estimated from correlation of three independent sub-events

Elliptic Flow – Event Plane Method

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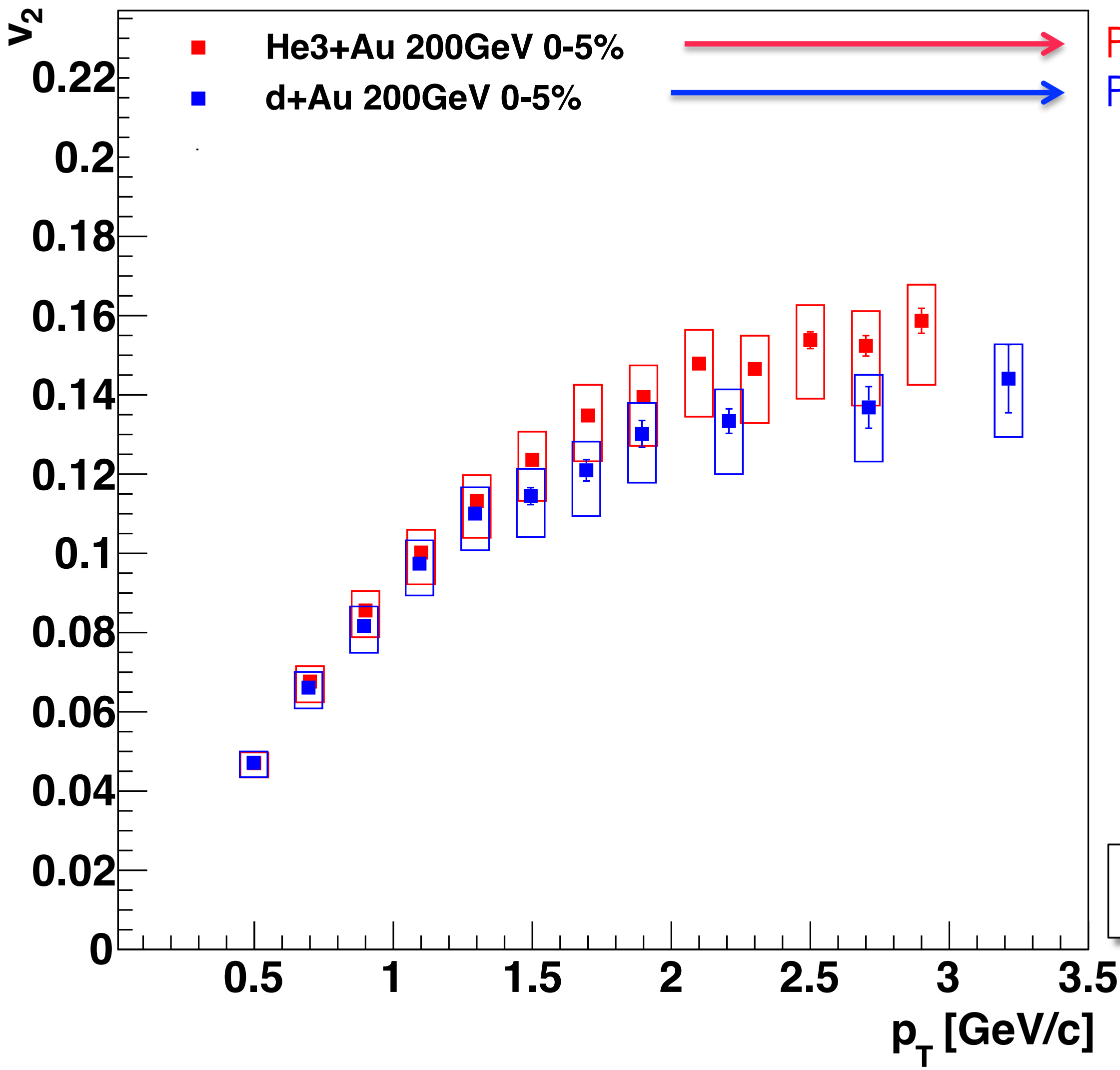

Phys. Rev. Lett. 115, 142301 (2015)

Phys. Rev. Lett. 114, 192301 (2015)

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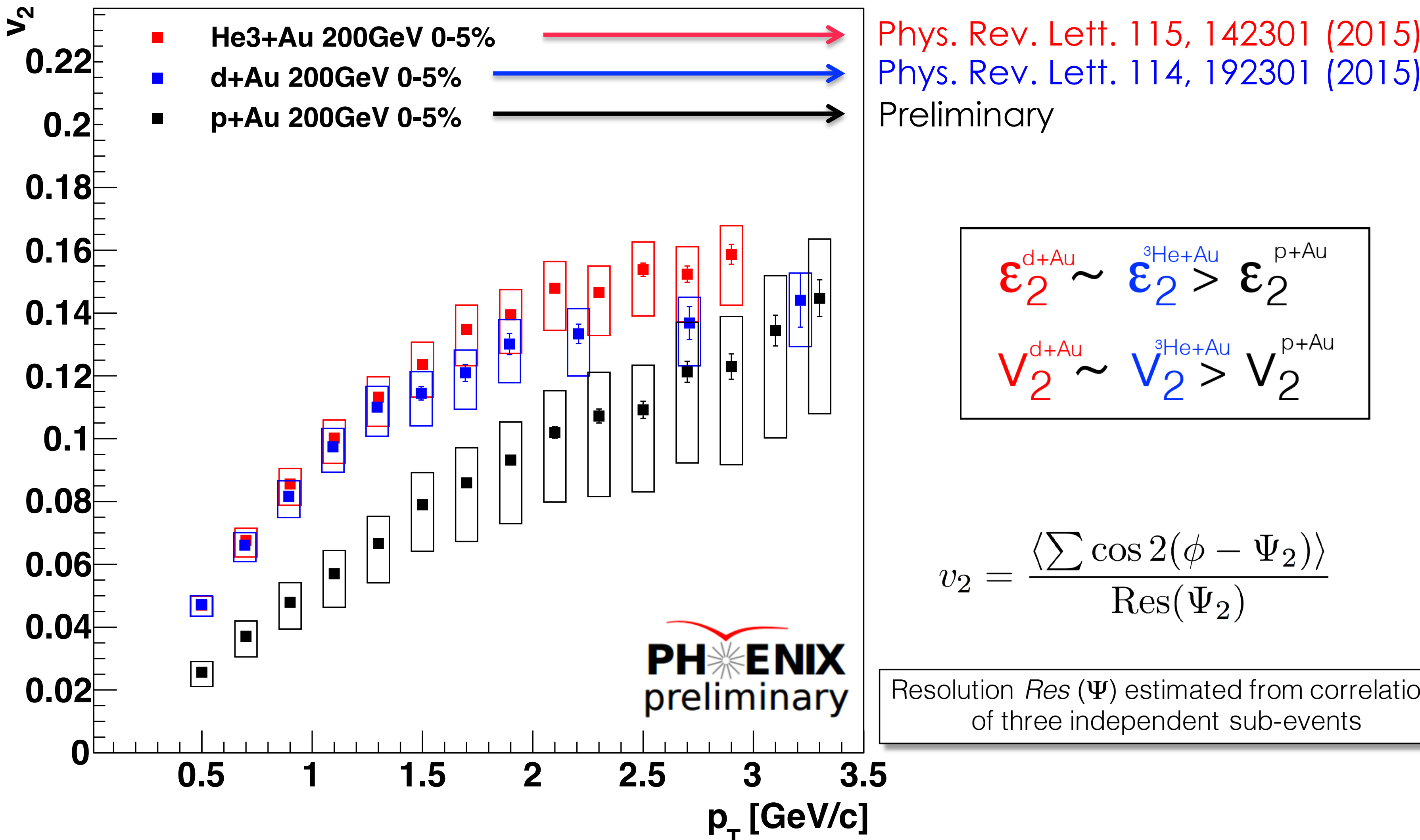


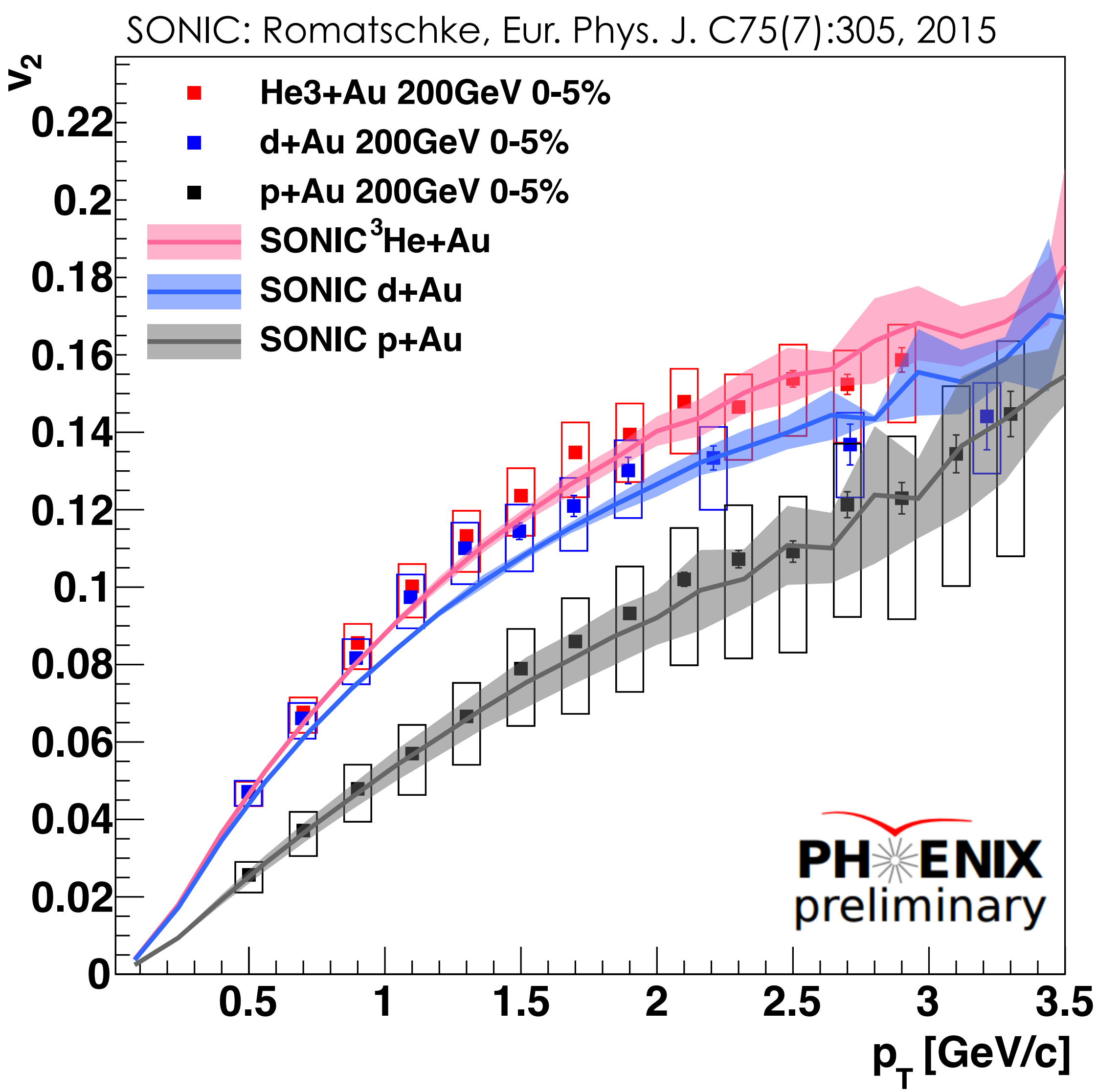
$\varepsilon_2^{d+Au} \sim \varepsilon_2^{3He+Au} > \varepsilon_2^{p+Au}$

$V_2^{d+Au} \sim V_2^{3He+Au} > V_2^{p+Au}$

$$v_2 = \frac{\langle \sum \cos 2(\phi - \Psi_2) \rangle}{\mathrm{Res}(\Psi_2)}$$

Resolution *Res* (Ψ) estimated from correlation of three independent sub-events

Sonic: Viscous Hydro Model



MC Glauber initial conditions

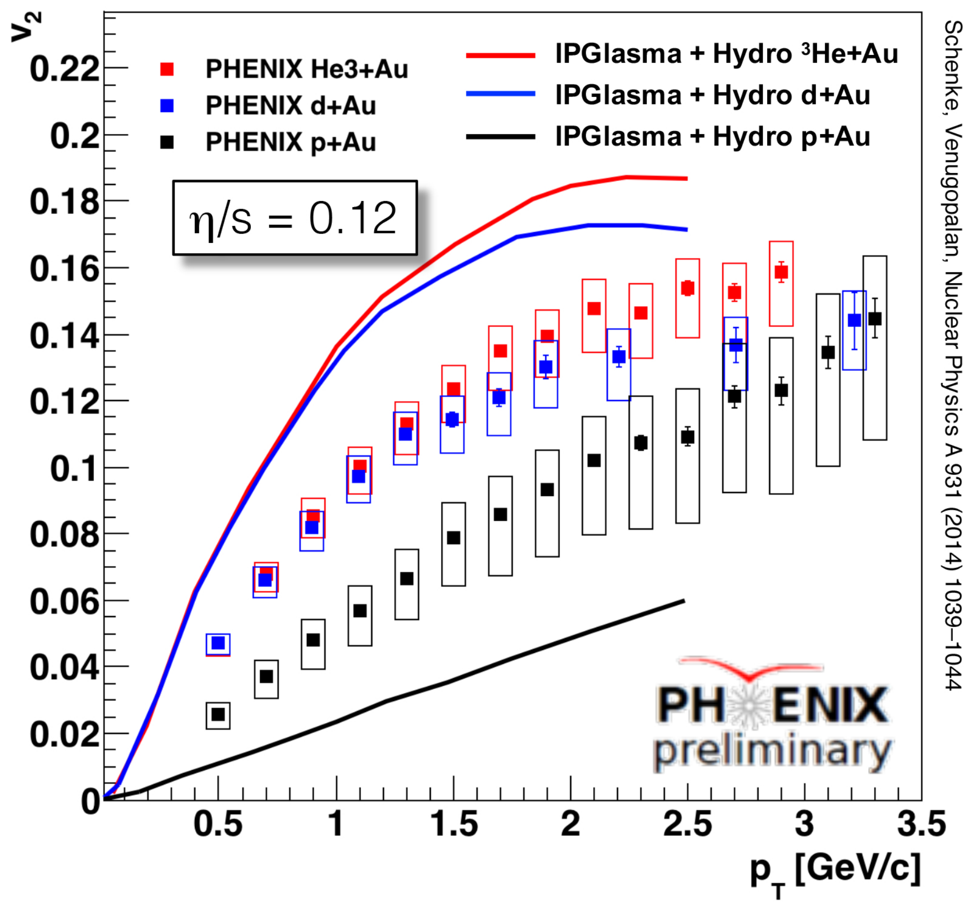
Relativistic viscous hydrodynamics

Cooper-Frye hadron cascade

Remarkable Agreement!

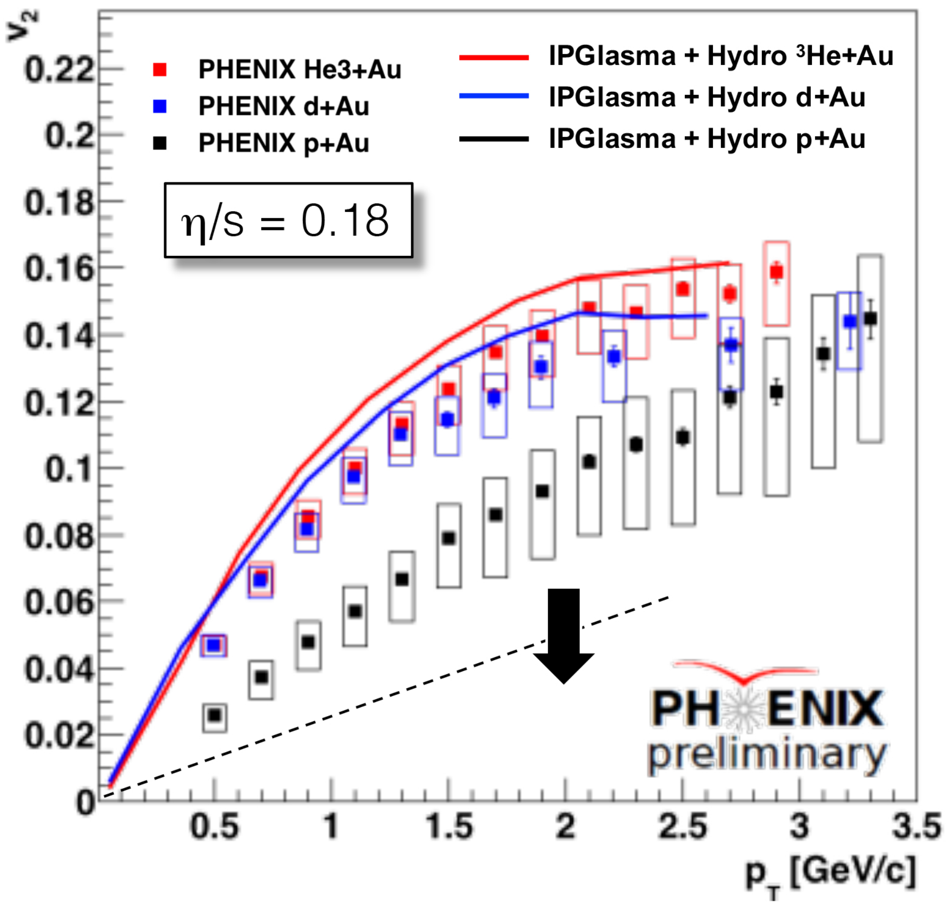
Hydro with IP Glasma Initial Conditions

d+Au and ^{3}He+Au are overpredicted
p+Au is underpredicted



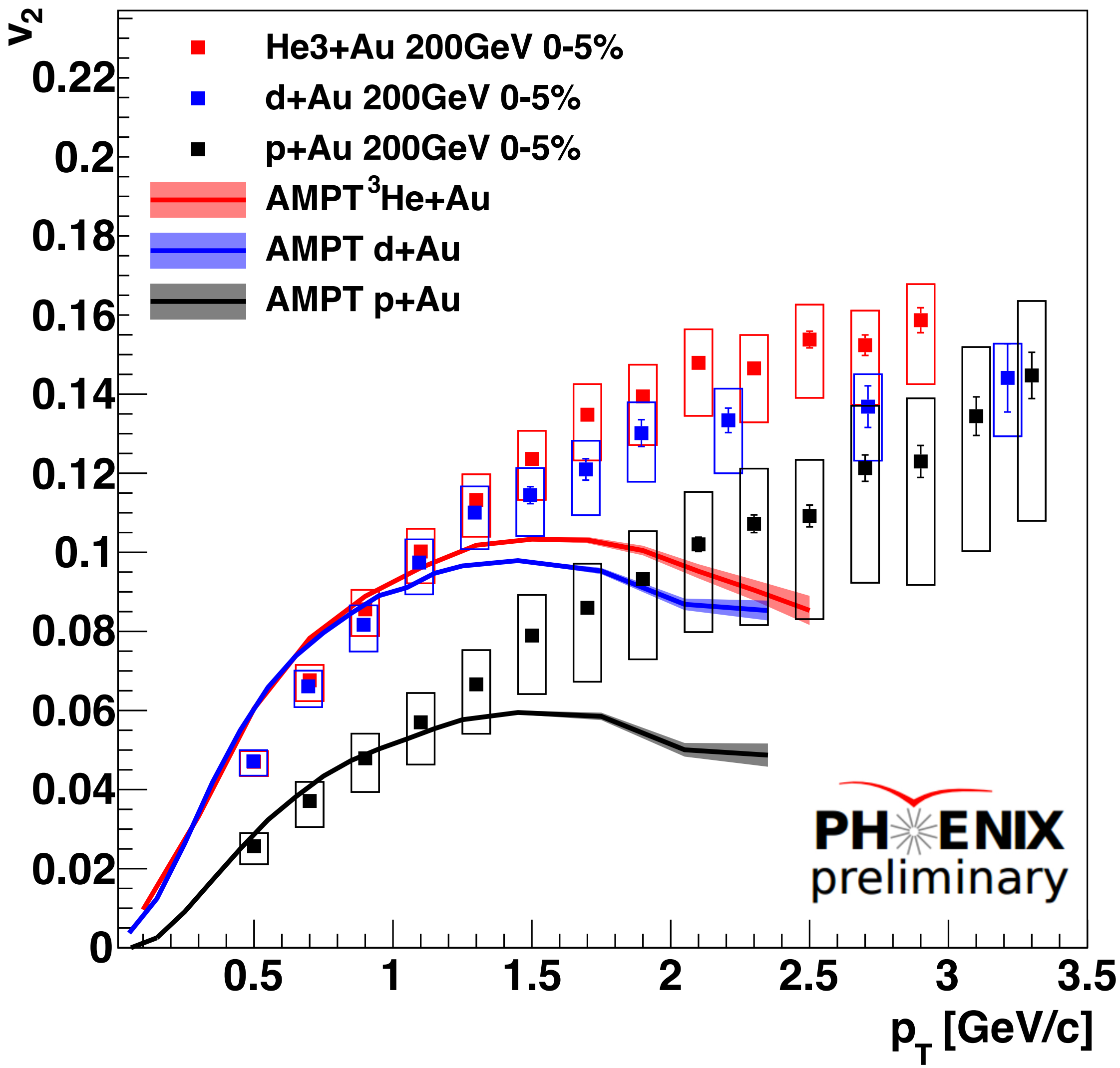
Hydro with IP Glasma Initial Conditions

Changing η/s makes all curves move in the same direction



AMPT: Partonic Scattering Model

AMPT: Orjuela-Koop, Adare, McGlinchey, Nagle, Phys. Rev. C 92, 054903 (2015)



MC Glauber initial conditions

String Melting

Partonic Scattering
$\sigma = 1.5$ mb

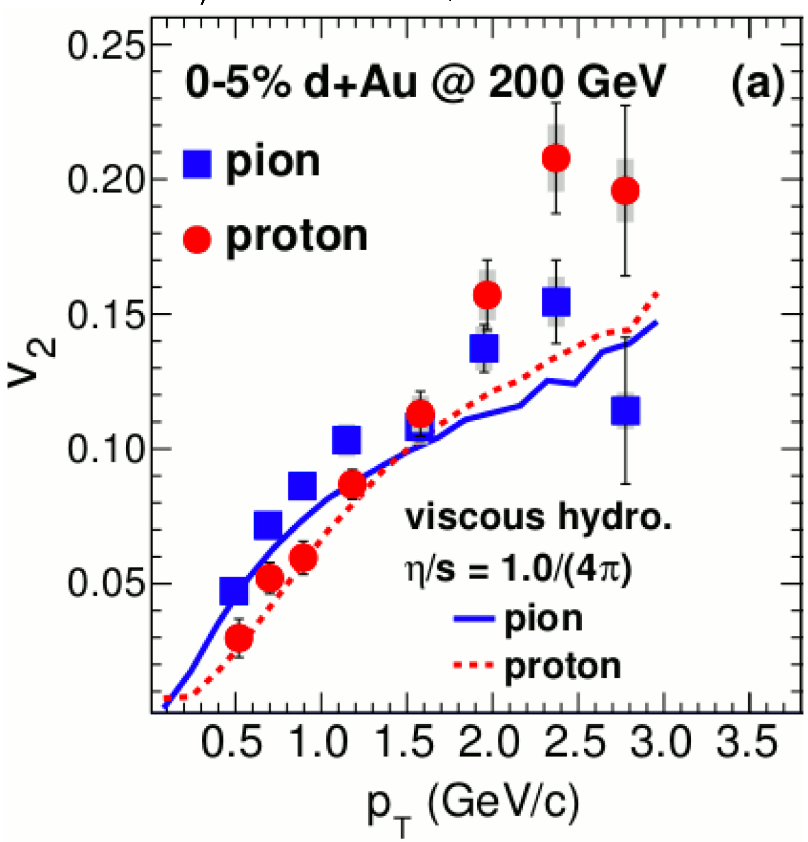
Spatial Coalescence

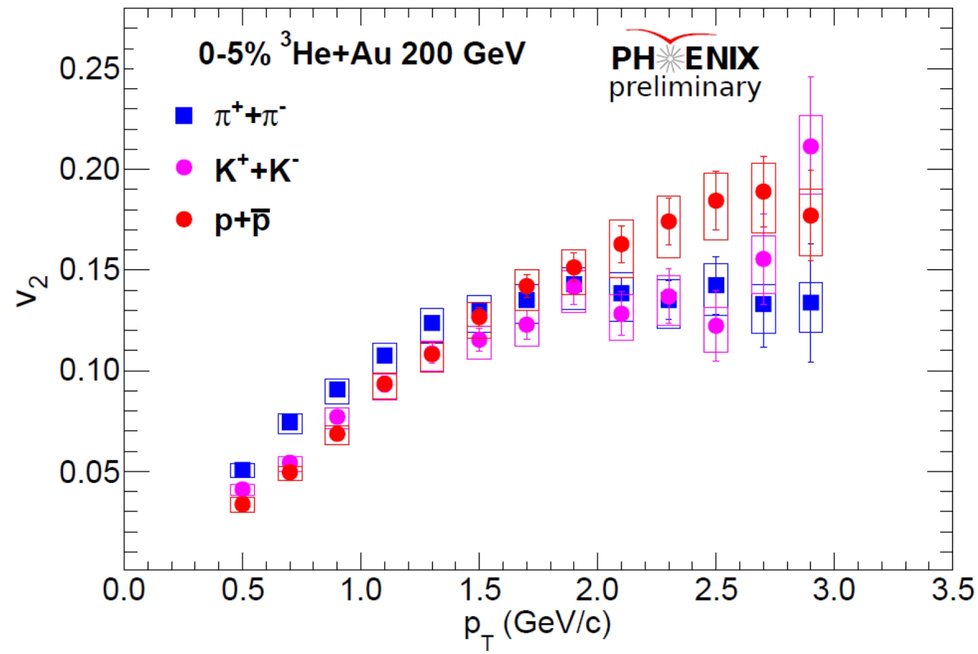
Hadronic Scattering

Elliptic Flow Mass Ordering

PHENIX Data

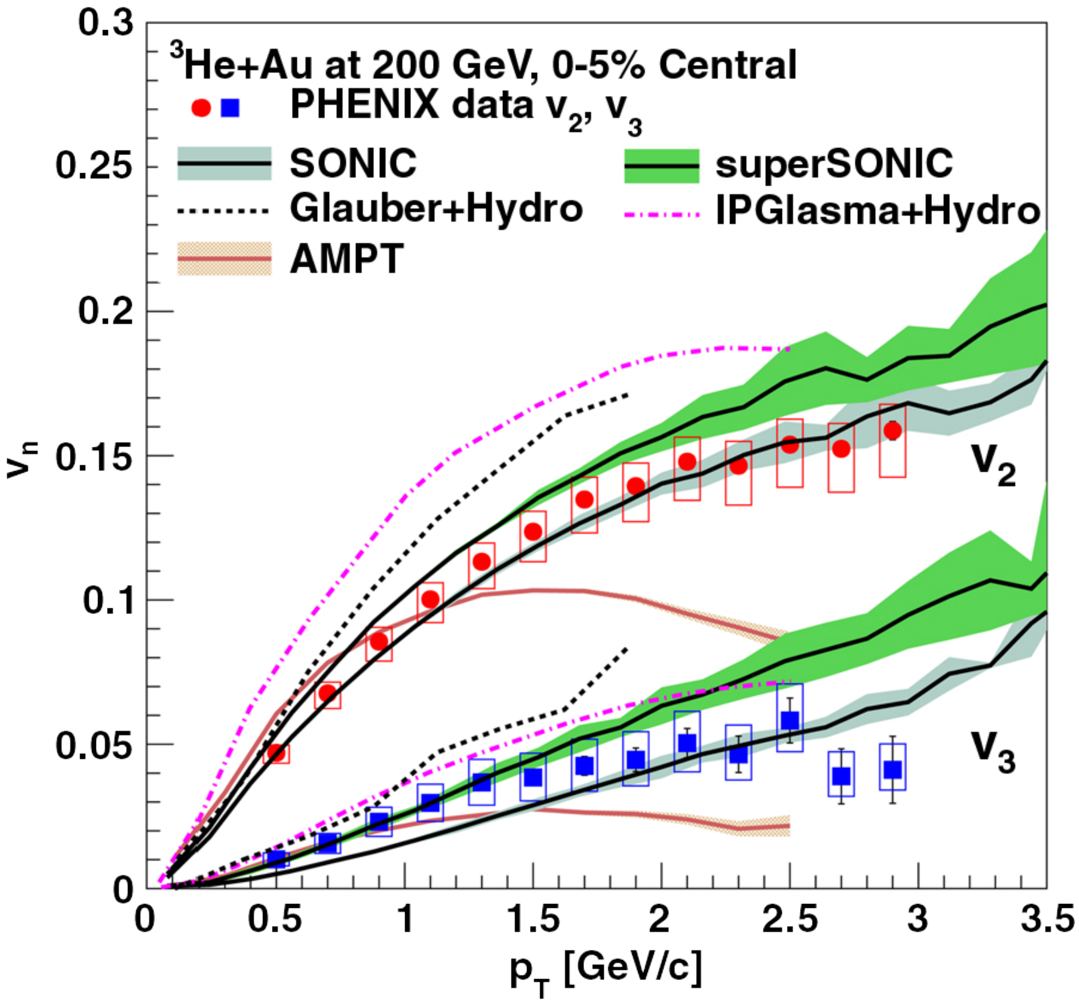
Phys. Rev. Lett. 114, 192301





As in A+A collisions, elliptic flow mass ordering is a feature of small systems

Triangular Flow 3He+Au

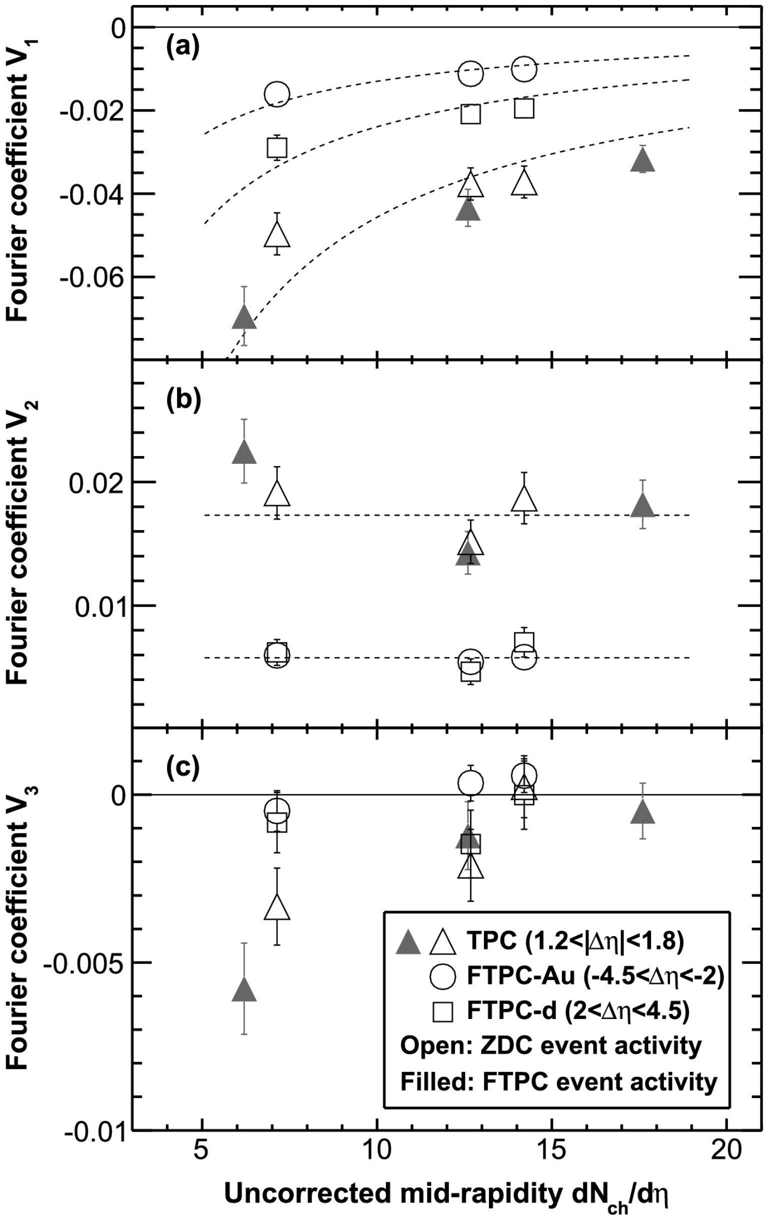


v_3 Measured in central 3He+Au at 200GeV

superSONIC
=
SONIC + preequilibrium phase

v_3 expected to be measured with run 16 d+Au 200GeV

v_n in d+Au 200GeV from STAR



Physics Letters B Volume 747, 30 July 2015, Pages 265–271

In agreement with PHENIX in overlap region

Small Systems Experiments

Change Geometry

Change Energy

- Geometry drives flow in small systems

- Anisotropy measurements in good agreement with hydro models

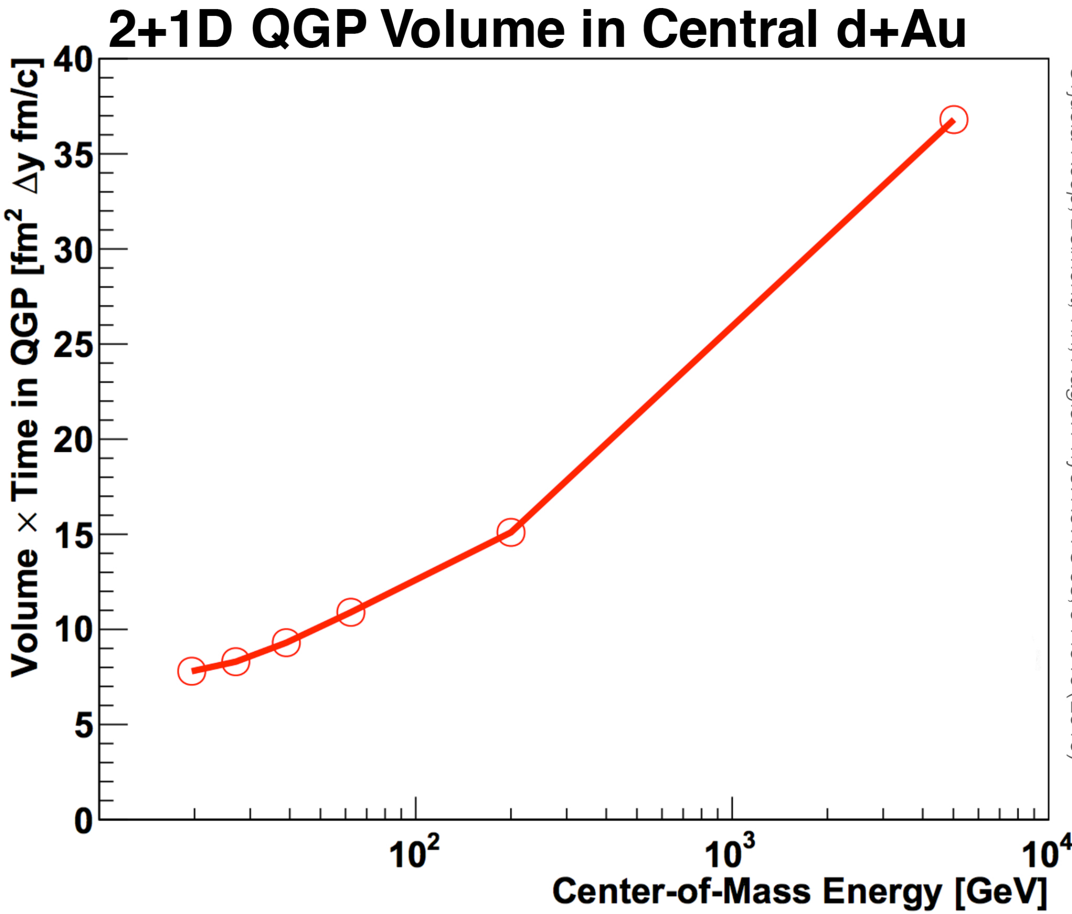
Small Systems Experiments

Change Geometry

Change Energy

- Geometry drives flow in small systems
- Lower beam energy
- Anisotropy measurements in good agreement with hydro models
- Look for response in v_n measurements

Going Down in Energy

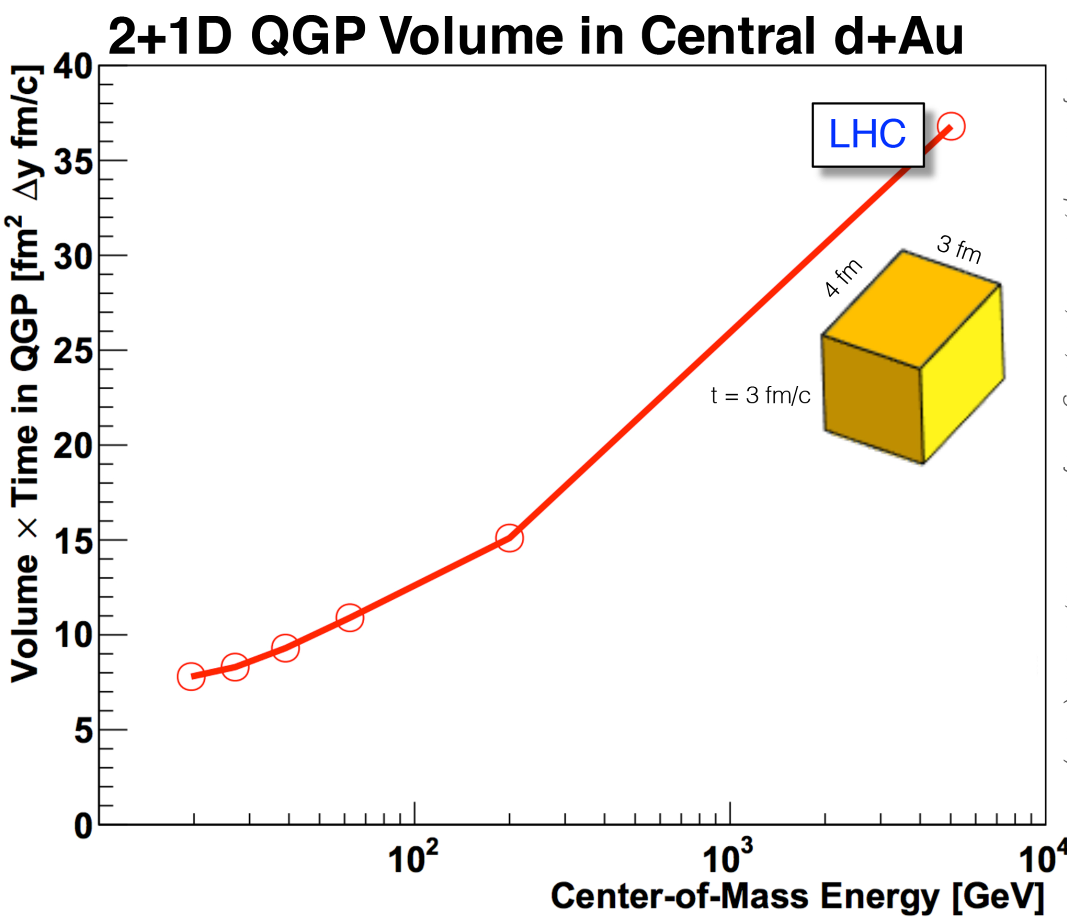


Orjuela-Koop, Belmont, Yin, Nagle: Phys. Rev. C 93, 044910 (2016)

In hydro:

Sum spacetime volume of all fluid elements hotter than the transition temp

Going Down in Energy



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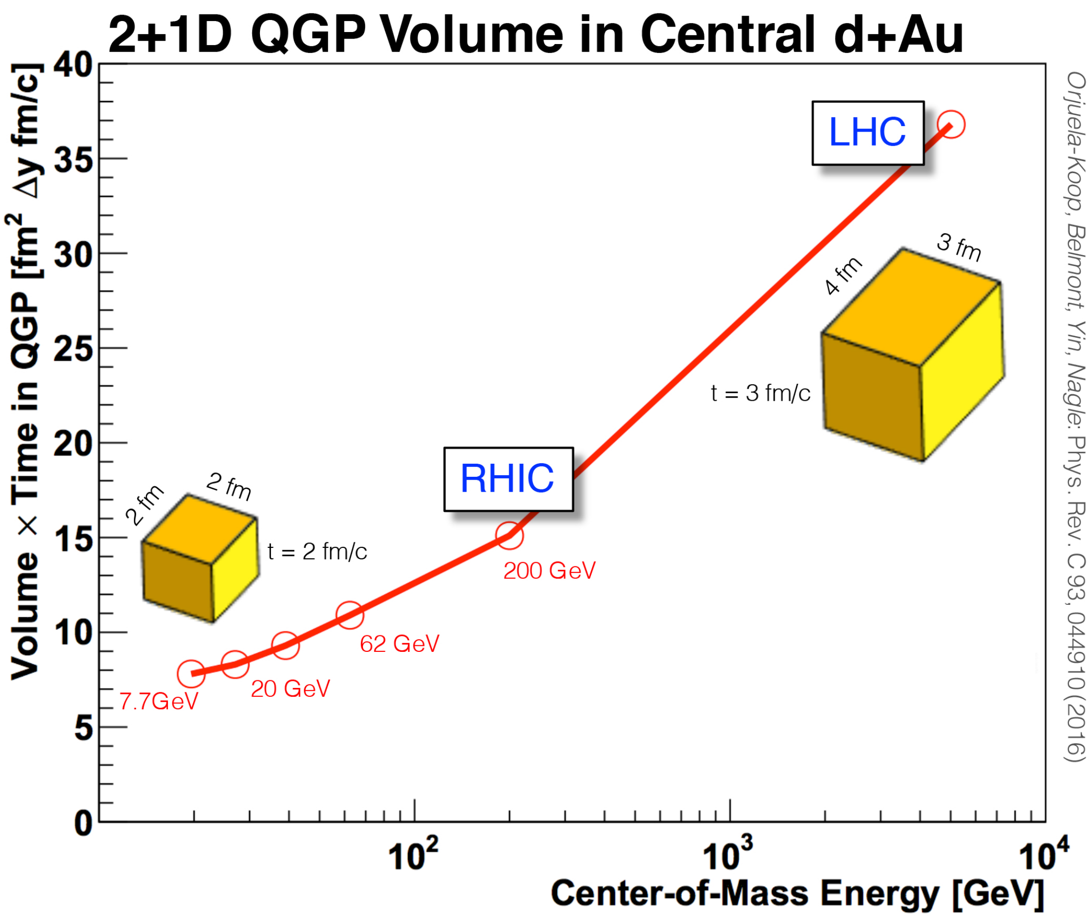


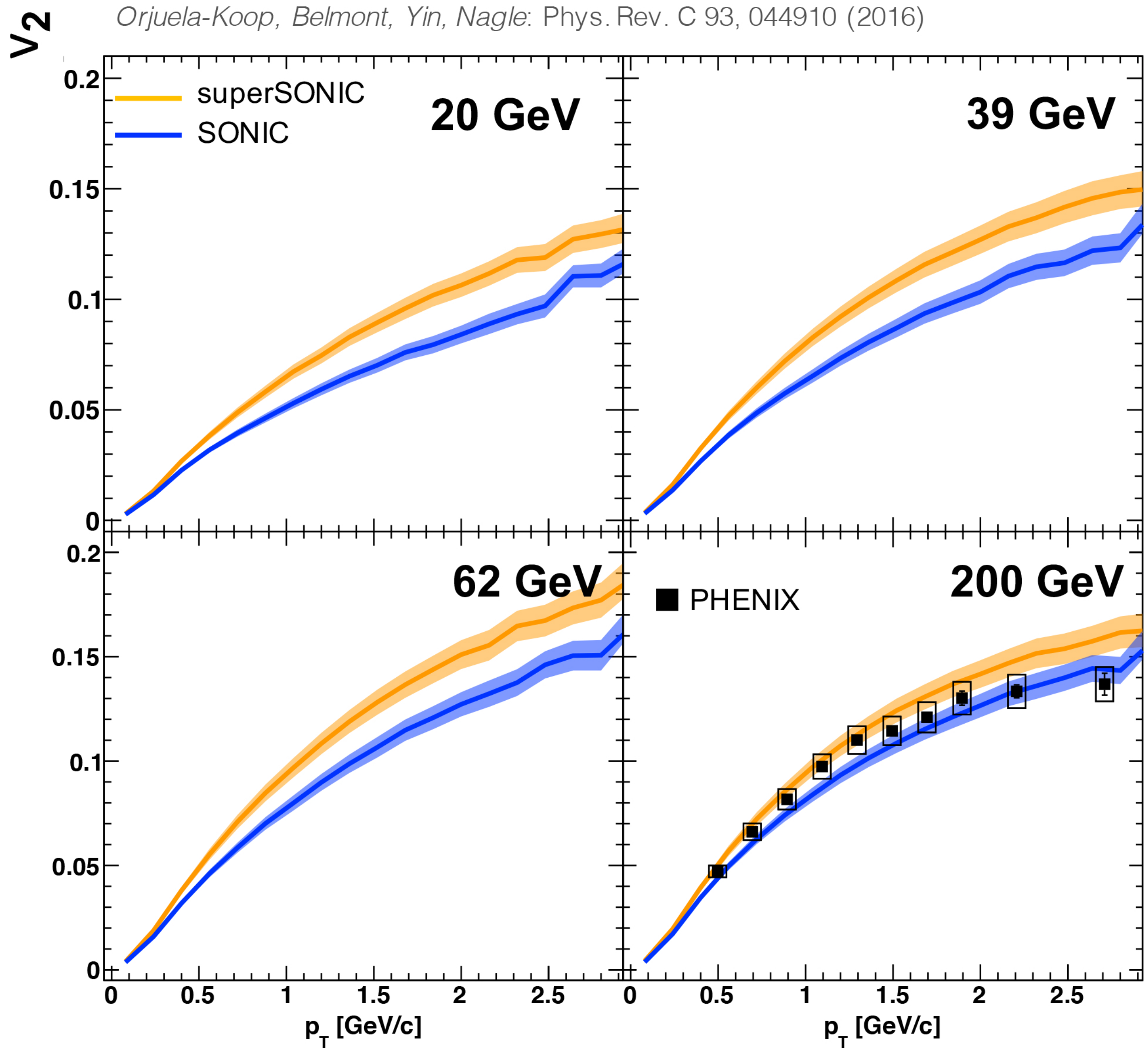
In hydro:

Sum spacetime volume of all fluid elements hotter than the transition temp

Lowering collision energy lowers the contribution from the QGP phase

Run 16 d+Au Beam Energy Scan

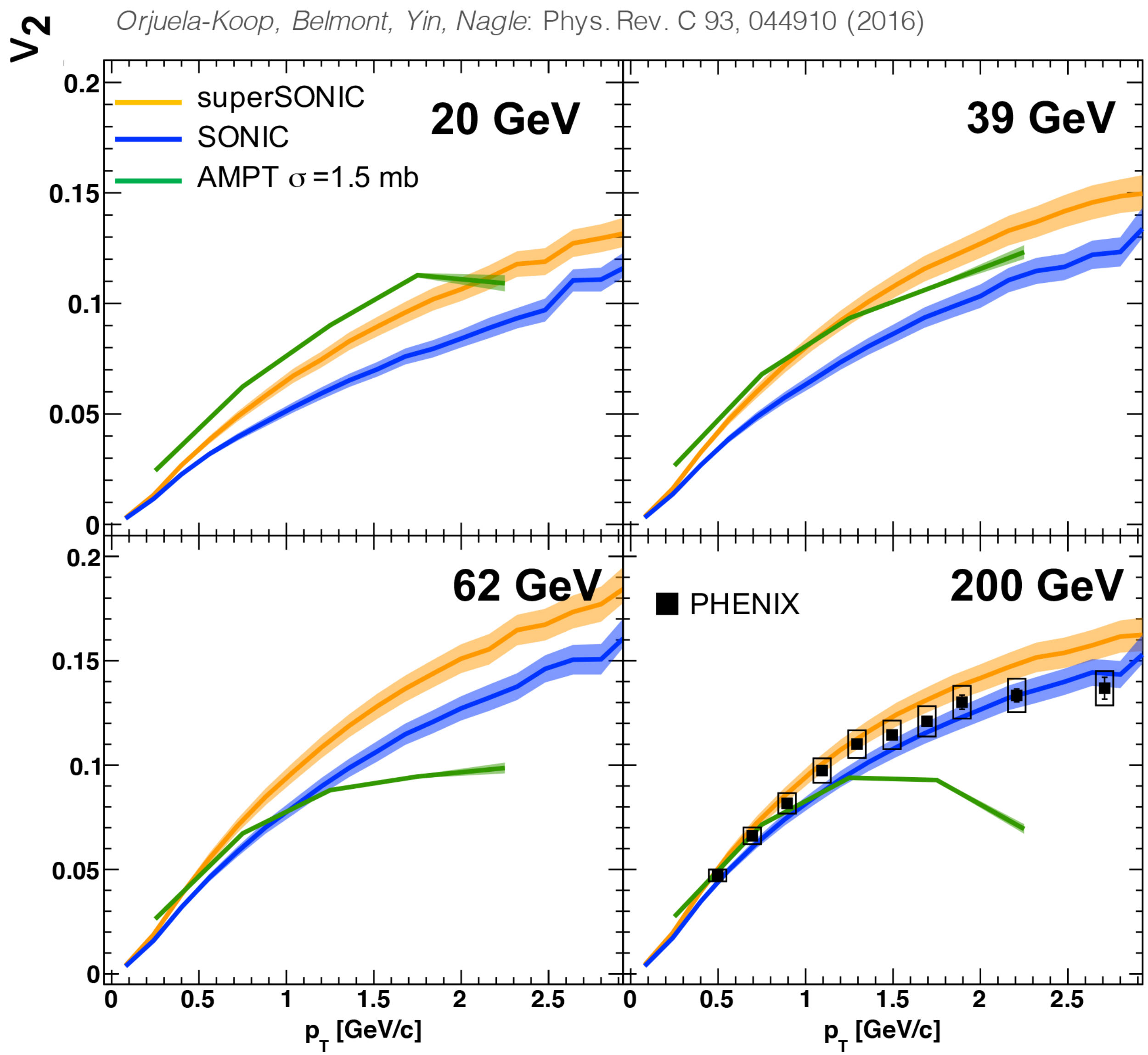
Orjuela-Koop, Belmont, Yin, Nagle: Phys. Rev. C 93, 044910 (2016)



Hydro With Pre-Equilibrium

Hydro Without Pre-Equlibrium

Run 16 d+Au Beam Energy Scan



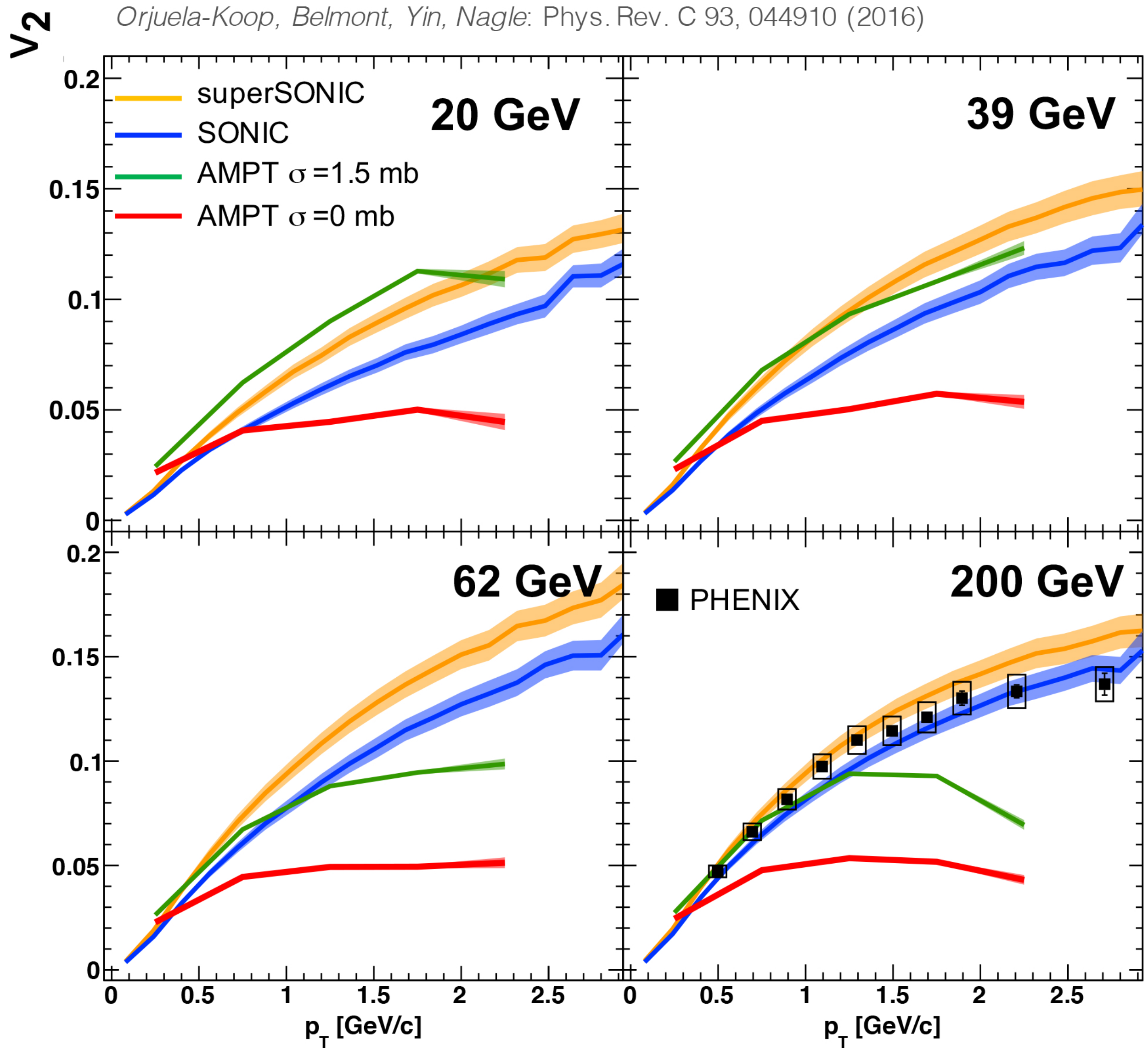
Hydro With Pre-Equilibrium

Hydro Without Pre-Equlibrium

AMPT Parton + Hadron

Run 16 d+Au Beam Energy Scan

Orjuela-Koop, Belmont, Yin, Nagle: Phys. Rev. C 93, 044910 (2016)



Hydro With Pre-Equilibrium

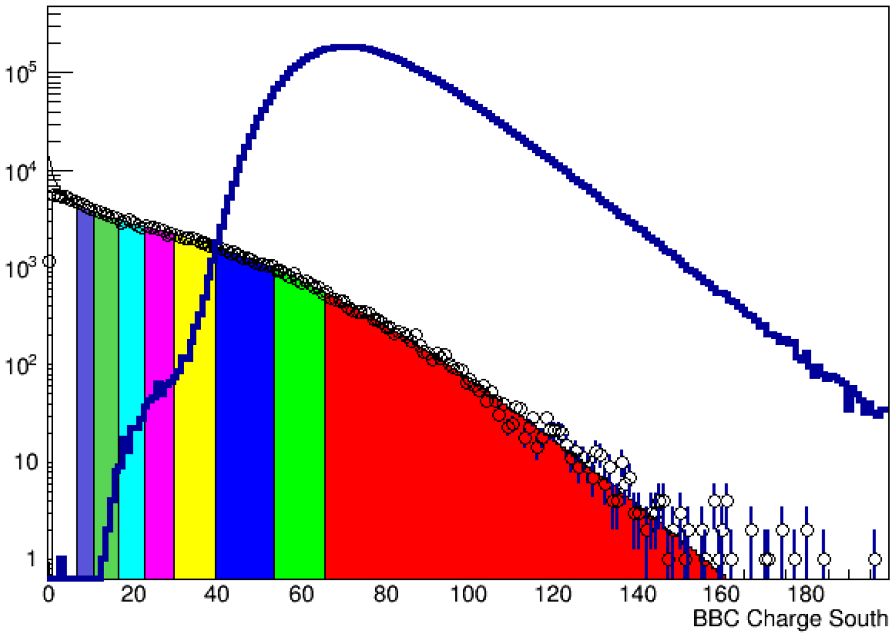
Hydro Without Pre-Equlibrium

AMPT Parton + Hadron

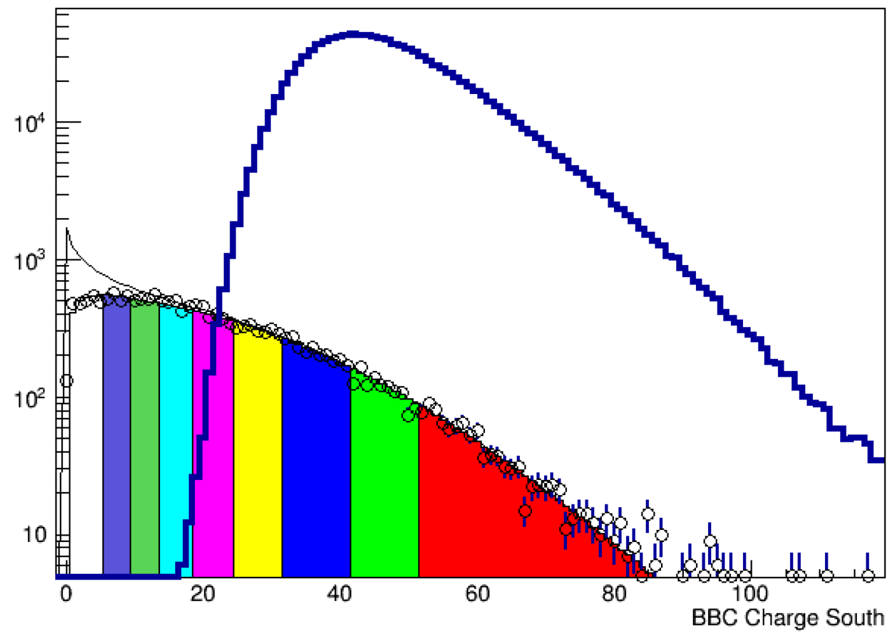
AMPT Hadron Only

Run 16 d+Au Beam Energy Scan

200 GeV



62 GeV



Central trigger (0-5%) ~ 1.3 x 10^9 events
Min Bias trigger (0-5%) ~ 0.8 x 10^7 events

Small Systems Experiments Summary

Change Geometry	Change Energy
Geometry drives flow in small systems	Models predict significant v_2 for all energies in beam energy scan
Anisotropy measurements in good agreement with hydro models	Measurements coming soon!

Thank You